DIAGNOSTIC SYSTEM AND METHOD FOR TRANSDUCERS

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Field of the Invention

[0002] The present invention relates generally to transducers, and more particularly to a diagnostic system and method for use with transducers.

Background

[0003] A transducer is a device that converts energy from one form into another form. One particular class of transducers provides an electrical output signal in response to an acoustic input, or an acoustic output in response to an electrical input. In the field of underwater acoustics, a transducer that is designed to accomplish the former function—produce an electrical output in response to an acoustic input—is called a "hydrophone." A transducer that generates an acoustic output signal in response to an electrical input is called a "projector." Hydrophones and projectors are commonly used for underwater ranging and detection, velocity measuring, imaging, *etc.*; that is, sonar.

[0004] Sonar arrays typically include multiple transducers and can take a variety of forms. In some arrays, such as the one depicted in Figure 1, multiple transducers **102** are precisely spaced apart in a linear array **100** and towed behind a ship or submarine (not depicted). In some other arrays, such as are sometimes used in submarines, multiple transducers **102** are arranged in 2d arrays **200** (*e.g.*, square, rectangular, *etc.*) and installed in the hull **206** of the submarine (*see*, Figure 2). In certain sonar arrays, some of the transducers function as projectors while others function as hydrophones. In some other arrays, all transducers function as hydrophones, and in still other sonar arrays, all transducers function as projectors and hydrophones.

[0005] In active sonar arrays, such as sonar arrays **100** and **200**, transducers that are operating as projectors convert electrical energy that is generated by sonar

transmitter **104** into sound waves. The sound waves are launched into the surrounding water. The sound waves, which collectively propagate as an acoustic beam, travel through a region of the water in a beam to perform the intended sonar function.

[0006] By appropriately controlling phase and amplitude of the electrical signals that are applied to individual projectors in the sonar array, one or more acoustic beams having appropriate shapes can be formed and steered to scan a particular region. The region that is acoustically imaged is referred to as the "ensonification field." Objects that are located within the ensonification field reflect or scatter the acoustic beam(s), thereby generating return sound signals or "echo."

[0007] The echo is received by transducers **102** in the array that are operating as hydrophones. The hydrophones convert the echo to electrical signals, which are transmitted to sonar receiver **105**. The electrical signals, which are representative of the echo, are then processed and the results are displayed in a form that is useful by sonar personnel for identifying, locating, *etc.*, the ensonified objects.

[0008] Sometimes, the performance of a sonar array degrades over time. The degradation can result from partial or complete failure of one or more of the transducers (hydrophones) in the array. Historically, "electrical tone application" or "conductivity" tests have been used to identify malfunctioning transducers. These tests are limited, however, in their ability to identify partial malfunctions. Furthermore, these tests are generally not capable of quantifying the extent of the malfunction or predicting its affect on array performance. Once a malfunctioning transducer is identified via these techniques, it is either electronically removed from the array or physically replaced. But it might take an extended period of time before an opportunity to replace a transducer arises. And electronically removing one or more transducer(s) from a sonar array might reduce the capabilities (*e.g.*, power, sensitivity, *etc.*) of the array.

[0009] Furthermore, on occasion, sonar arrays comprising newly-manufactured transducers that have passed all standard factory test requirements do not perform as expected. Since the transducers have passed standard factory tests, and short of an autopsy, there is often little that can be done to determine which of the transducers in the array are faulty. Depending upon the extent of the performance deficit, the array is either deployed with compromised performance or replaced before deployment with a concomitant delay in mission readiness.

[0010] It would, therefore, be desirable to have a new diagnostic method and system that exhibits one or more of the following attributes:

- Is more reliable and capable than prior-art techniques at identifying partially malfunctioning transducers.
- Is able to quantify the effect that a malfunctioning transducer will have on the performance of a transducer array.
- Provides data that can be used by processing electronics as a "calibration factor" to correct for the degradation of one or more transducers in the array.
- Provides data that can be used to yield the best performance from a given group of transducers by selectively positioning the "best" transducers at the most critical positions in the array.
- Complements or replaces standard factory-acceptance tests for transducers.

Summary

[0011] Some embodiments of the invention provide a diagnostic method and system for use with transducers that exhibits one or more of the above-listed attributes.

[0012] In accordance with the illustrative embodiment, a diagnostic method for use with *multi-element* transducers comprises:

- determining an acoustic center of a transducer; and
- determining an offset of the determined acoustic center from a theoretical acoustic center.

[0013] In accordance with the illustrative embodiment, a diagnostic system for use with *multi-element* transducers comprises:

- a projector, wherein the projector generates a sound; and
- a mechanical fixture, wherein the fixture aligns the projector with the transducing elements (in the transducer) so the projector selectively ensonifies each of the transducing elements.

[0014] In some embodiments utilizing the illustrative diagnostic system, the operation of determining an acoustic center of a transducer includes the sub-operations of:

- aligning a projector over each transducing element;
- ensonifying each transducing element;
- measuring the output from each ensonified transducing element;
- calculating the acoustic center as a weighted average of the output from the transducing elements (as a function of their position in the arrangement of transducing elements).

[0015] The acoustic center, as determined from the illustrative method and system, and its offset from the theoretical acoustic center of the transducer, can be used for a variety of purposes that define variations of the illustrative method. For example, the offset can be used for any one or more of the following purposes, among any others:

- to predict the performance (deficit) of an array;
- to validate newly-manufactured transducers;
- to selectively position transducers in an array; and
- to correct signal processing calculations for the observed offset in the acoustic center.

[0016] In accordance with a further aspect of the invention, a transducer array with variably-positionable transducers is disclosed. This embodiment takes advantage of the fact that an actual acoustic center of a transducer is calculated to appropriately position the transducers relative to one another in an array.

[0017] These and other features of the illustrative embodiment of the present invention are described in detail in the following Detailed Description and depicted in the appended Drawings.

Brief Description of the Drawings

[0018] **Figure 1** depicts a linear sonar array in the prior art.

[0019] **Figure 2** depicts a 2d sonar array in the prior art.

[0020] **Figure 3** depicts a multi-element transducer in the prior art.

[0021] **Figure 4** depicts diagnostic method **400** for use with transducers in accordance with the illustrative embodiment of the present invention.

[0022] **Figure 5** depicts a side view of a multi-element transducer in the prior art.

[0023] **Figure 6** depicts diagnostic system **500** in accordance with the illustrative embodiment of the present invention.

[0024] **Figure 7** depicts a template for use with diagnostic system **500**.

[0025] **Figure 8** depicts sub-operations of operation **402** of method **400**, and additional optional operations in variations of method **400**.

[0026] **Figure 9** depicts a pictorial representation of the performance of an array of tranducing elements of a transducer, wherein the representation exhibits a high degree of symmetry in the output of the transducing elements, indicative of good transducer performance.

[0027] **Figure 10** depicts a pictorial representation of the performance of an array of tranducing elements of a transducer, wherein the representation exhibits a high degree of asymmetry in the output of the transducing elements, indicative of unacceptable transducer performance.

[0028] **Figure 11** depicts an array having variably-positionable transducers.

Detailed Description

[0029] The illustrative embodiment of the present invention is a diagnostic method and system for use with transducers, such as are used in underwater acoustics, medicine, aeronautics, and the like. The illustrative embodiment is suitable for use only with *multi-element* transducers. Use of the illustrative embodiment is independent of the operating principle of the transducer; that is, it can be used with multi-element transducers that are based on a piezoelectric, magnetostrictive, or other principles of operation. Furthermore, the illustrative embodiment is useful as a diagnostic for transducers regardless of their mode of operation (*e.g.*, hydrophone or projector, *etc.*).

[0030] The terms and phrases listed below are defined for use in this specification as follows:

"**Acoustic Center**" means (1) the origin from which an acoustic field that is generated by a transducer (*e.g.*, projector, *etc.*) is considered to have emanated or (2) the point at which an echo is considered to be received by a transducer (hydrophone, *etc.*).

"**Transducing Element**" means a functional element within a transducer that is responsible for converting one form of energy into another. For example, some

tranducers will incorporate a plurality of piezoelectric transducing elements. These elements, when compressed, as when exposed to a pressure wave, generate a voltage. Conversely, when an electric field is applied to these elements, they expand or contract in certain directions. Other transducers will incorporate a plurality of magnetostrictive transducing elements.

[0031] Figure 3 depicts conventional multi-element transducer **102**. The transducer comprises a plurality of individually, electrically-connected, internal transducing elements **308**, which are typically organized in a symmetrical arrangement, such as arrangement **310**.

[0032] The acoustic center of transducer **102** is nominally located at point **312**, which, in arrangement **310**, is located at the geometric center of arrangement **310**, as is often the case. In sonar arrays (*e.g.*, sonar array **100**, **200**, *etc.*), which have a plurality of transducers **102**, there is a precise spacing between the acoustic center of the various transducers.

[0033] It is important that the acoustic center of each transducer in an array is precisely located, because these locations form a basis for signal processing calculations (both for the transmitted acoustic beams and the received echo). Indeed, the accuracy of signal processing calculations depends on it. As a consequence, if one or more of transducers **102** is having an operational problem that causes its acoustic center to shift, then the performance of the array, in terms of its ability to accurately locate, range, identify, or obtain other information about objects, might be compromised. This is explained in more detail below.

[0034] With continued reference to Figure 3, a failure mode, deterioration, or manufacturing defect can occur in which some of transducing elements **308** partially or completely fail (*e.g.*, due to delamination or failure or disconnect of transducing elements **308**). If this occurs, the acoustic center of the transducer shifts. As discussed above, this can affect that accuracy of the information obtained from array **100**.

[0035] Figure 4 depicts method **400** in accordance with the illustration embodiment of the present invention. According to operation **402** of method **400**, the acoustic center of a multi-element transducer is determined. Figure 8 depicts sub-operations **802** through **808** of operation **402** as well as additional optional operations used in

variations of illustrative method **400**. Context for the description of method **400** is provided with reference to Figures 6 and 7, which depict an illustrative embodiment of diagnostic system **600** for implementing method **400** on prior-art, multi-element transducer **514**.

[0036] Referring now to Figure 5, prior-art transducer **514** includes transducer housing **516**, transducing elements **517** disposed within housing **516**, base **518** and mounting bolts **520**. The base and mounting bolts are for installing transducer in an internal (*e.g.*, hull, *etc.*) -type sonar array.

[0037] System **600** depicted in Figure 6 includes test projector **622** and mechanical fixture **624**. Projector **622** is electrically coupled to signal generator **630** and receives a signal therefrom. The projector emits sound in response to this electrical input. The sound generated by projector **622** is directed toward transducing element **517-3** of transducer **514**.

[0038] Referring now to Figures 6 and 7, mechanical fixture **624** is an alignment device that aligns projector **622** over the center of underlying transducing element **517** of the transducer. This ensures that the sound that is emitted by projector **622** is directed to a specific transducing element. In the illustrative embodiment, fixture **624** is implemented as grid, which defines a plurality of grid elements **626**. When fixture **624** is properly aligned over transducer **514**, elements **626** of the grid overlie the various transducing elements **517** of transducer **514**. In some embodiments, alignment fiducials are provided to align fixture **624** with transducing elements **517** in the transducer. For example, in the illustrative embodiment, mounting bolts **520** are used as an alignment fiducial wherein members **628** of fixture **624** cooperate with the mounting bolts to align grid elements **626** to the underlying transducing element **517**. Projector **622** is appropriately dimensioned to cooperate with fixture **624**. It will be appreciated that other arrangements can be used. For example, although more complicated, transducer **514** can be positioned on a x-y stage (not depicted), wherein each transducing element **517** is brought into alignment a projector that is held stationary.

[0039] In some embodiments, projector **622** is moved from grid element to grid element to ensonify each underlying transducing element **517**, one at a time. In some other embodiments, multiple projectors are used to simultaneously ensonify two or more transducing elements. In some embodiments, such as the one depicted in Figure 7, not all grid elements **626** overlie a transducing element **517**. In Figure

7, grid elements **626** that do not overlie a transducing element are indicated by an "x." In some embodiments, mechanical fixture **624** is configured so that grid elements **626** that do not overlie a transducing element are blocked (*e.g.*, not open, *etc.*). To ensure good acoustic coupling of projector **622** to each transducing element **517**, a suitable acoustic grease or other means is advantageously used.

[0040] In response to the sound that it receives, each transducing element **517** generates an output, which is typically measured as a voltage. The output from each transducing element is measured by measurement device **632**, which in the illustrative embodiment is a spectrum analyzer.

[0041] The output from measurement device **632** is collected and then processed in processor **634**. In some embodiments, processor **634** calculates the acoustic center of the transducer under test. This can be done, for example, by calculating a weighted average of the output characteristic (*e.g.*, voltage, *etc.*) of each transducing element **517** as a function of a relative location of the element, in known fashion.

[0042] In some embodiments, processor **634** calculates the offset of the actual acoustic center (as determined from the present method and system) from the theoretical acoustic center (typically the geometric center of the arrangement of transducing elements **517**), as per operation **404** of method **400**. Processor **634** provides an indication of the actual acoustic center or the offset or both. The acoustic center or offset is presented as is convenient, for example, as a Cartesian coordinate or a polar coordinate, with the coordinate system centered at the geometric center of the arrangement of transducing elements.

[0043] Returning now to the description of operation **402** of method **400** (determine the acoustic center of the transducer), system **600** can be used to carry out sub-operations **802** through **808** for implementing operation **402**, including:

- Sub-operation **802**: Align projector over transducing element;
- Sub-operation **804**: Ensonify transducing element;
- Sub-operation **806**: Measure output from ensonified transducing element; and
- Sub-operation **808**: Calculate the acoustic center as a weighted average of the output from the transducing element.

[0044] Additionally, in some embodiments, as per optional operation **810**, the output obtained from transducing elements **517** is represented pictorially. Such a pictorial representation can be displayed electronically by a monitor (*e.g.*, computer display, *etc.*) or printed. An example of such a pictorial representation is depicted in Figures 9 and 10.

[0045] Figure 9 depicts a pictorial representation of the electrical output from a first transducer. The pictorial representation comprises array **936** of "pixels" **938**. The electrical output (*e.g.*, voltage, *etc.*) is represented by the color of each pixel, which, in order of descending electrical output are:

> R (red) > R/O (red-orange) > O (orange) > Y (yellow) > Y/G (yellow-green) > G (green) > B (blue) > P/B (purple-blue) > P (purple).

[0046] In some embodiments, there is a one-to-one correspondence between pixels **938** and transducing elements **517**. That is, the color of a pixel is representative of the electrical output of a corresponding transducing element. But in some other embodiments, there is not a one-to one correspondence between pixels and transducing elements. For example, in some embodiments, each pixel represents an average of the output of two adjacent pixels, *etc.*

[0047] Of more importance than the specific color of a given pixel in array **936** is the symmetry, or lack thereof, of the color pattern that is presented by array **936.**

[0048] In particular, as can be seen in Figure 9, the output of the transducing elements defines a nearly symmetric pattern. As a consequence, the measured acoustic center of the first transducer aligns with the theoretical (and in this case geometric) center of the array of transducing elements. This is excellent measured performance, which evinces a normally-operating transducer.

[0049] Figure 10 depicts a pictorial representation of the electrical output from a second transducer. The output of the transducing elements defines a severely asymmetric pattern. This means that some of the transducing elements are not operating properly or they are otherwise disconnected from the electrical circuitry within the transducer. For this transducer, the measured acoustic center will not align with the theoretical acoustic center.

[0050] Although the information presented by the pictorial representation is qualitative, rather than quantitative, it provides a technician or other interested party with a sense of the "health" of a transducer. In fact, with experience, a glance at the

pictorial representation of a given transducer might be a sufficient basis to reject or accept it as suitable for a particular service.

[0051] While the information provided by the pictorial representation is qualitative, the determination of the actual acoustic center or determination of the offset from the theoretical acoustic center provides quantitative information that was not heretofore available. This information can be used in a variety of ways, as follows.

[0052] For example, in accordance with optional operation **812**, the offset can be used to predict the performance of a transducer array (*e.g.*, sonar, *etc.*). In particular, transducers typically have a defined and invariant location within a linear or 2d array. Signal processing calculations for beam forming or echo interpretation assume that the acoustic center of the transducer is the theoretical acoustic center. To the extent that the actual acoustic center of one or more of the transducers in such an array is offset from the theoretical center, then the performance of the array is degraded. Since the illustrative embodiment of the present invention calculates the amount of offset, it can be used to *quantify* the degradation in performance of the array. For example, in some embodiments in which the transducer array and signal processing provides a velocity-measuring system based on correlation processing, the offset of the acoustic center is used to predict error in the prediction of velocity.

[0053] In a further variation of method **400**, and in accordance with operation **814**, the offset of the acoustic center can be used during formal acceptance testing of newly-manufactured transducers. In particular, if the offset between the actual and theoretical acoustic centers exceeds some threshold, then the transducer is rejected. It will be appreciated that the threshold is application specific. For example, for some military sonar applications, the allowed offset will be quite low. For other military or civilian applications, the allowable offset will typically be relatively higher.

[0054] In yet a further variation of method **400**, and in accordance with operation **816**, information concerning the position of the acoustic center can be used to selectively position transducers in an array. Some positions in an array of transducers will be relatively more critical (*i.e.*, more heavily weighted) in terms of signal processing calculations. Once the offset of the acoustic center for each transducer in a group of transducers is known, the transducers can be selectively placed in the array for best performance.

[0055] In still another variation of method **400**, and in accordance with operation **818**, the offset in acoustic centers of a plurality of transducers in an array is used as a correction factor during signal processing calculations. In other words, to the extent that the offset in the acoustic center of each of the transducers in an array is known, those offsets can be used to correct the signal processing calculations (*e.g.*, beam-forming, echo interpretation, *etc.*), which are otherwise based on the assumption that the actual acoustic center is the theoretical acoustic center. This method aids in maintaining the performance of an aging transducer array until such time as it is desirable to physically replace the transducers in the array. And it can also be used to improve the performance of a sonar array.

[0056] A further aspect of the present invention is transducer array **1140** with variably-positionable transducers **1142**, as depicted in Figure 11.

[0057] In the prior art, the position of each transducer in an array is typically fixed. As a consequence, the *offset* between the theoretical acoustic center and the actual acoustic center is needed to determine the affect on performance and correct signal-processing calculations.

[0058] But by virtue of the illustrative method and diagnostic system, wherein an ability to calculate an actual acoustic center of the transducer is provided, there is a motivation to provide an array having transducers that are variably positionable.

[0059] Once in a desired position, transducers **1142** are held in place via gripping mechanism **1144**. Although depicted as a collar, the gripping mechanism can be implemented in as desired (*e.g.*, clamps, pins, *etc.*). Those skilled in the art will be capable of designing and building many different configurations of an array with variably-positionable transducers in light of the present teachings.

[0060] For variably-positionable arrays, and for fixed arrays as well, in some embodiments, methods that incorporate the various optional operations, such as operations **812** through **818**, are not based on a calculated *offset*, but rather the calculated *acoustic center*.

[0061] It is to be understood that the above-described embodiments are merely illustrative of the present invention and that many variations of the above-described embodiments can be devised by those skilled in the art without departing from the scope of the invention. It is therefore intended that such variations be included within the scope of the following claims and their equivalents.